Does knowledge base complexity affect spatial patterns of innovation? An empirical analysis of the upstream petroleum industry

Citation for published version:
Maleki, A & Rosiello, A 2019, 'Does knowledge base complexity affect spatial patterns of innovation? An empirical analysis of the upstream petroleum industry', *Technological Forecasting and Social Change*, vol. 143, pp. 273-288. https://doi.org/10.1016/j.techfore.2019.01.020

Digital Object Identifier (DOI):
10.1016/j.techfore.2019.01.020

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Technological Forecasting and Social Change

Does Knowledge Base Complexity Affect Spatial Patterns of Innovation? An Empirical Analysis of the Upstream Petroleum Industry

Abstract

Using network analysis, we investigate if an industry's complex and integrated knowledge base leads to a higher spatial concentration (or dispersal) of innovative activities. This is important because the extant literature provides competing claims about how knowledge base complexity impacts on the spatial distribution of industrial innovation. To help empirically resolve this issue, we draw on longitudinal data (1970-2010) on the upstream petroleum industry and build indexes of entropy and complexity to render knowledge base dynamics, assess the spatial concentration of innovation, and study industry structural transformations. We first find a correlation – once a crucial distinction between variety and systemic complexity is drawn - between increasing knowledge base complexity and higher concentrations of innovation at national level. In addition, we find that this increase was accompanied by a rising share of non-country of origin inventions owned by multinational companies, and that globally integrated service multinationals were best placed to manage this complexity and the integration of complementary knowledge fields. These findings, therefore, nuance the competing claims about the relationship between knowledge base complexity and spatial patterns of innovation. Furthermore, they reveal that although leading innovators may operate globally, their core innovative activities still remain located in a few key countries.

Key Words:
Upstream Petroleum, Knowledge, Complexity, Geography of Innovation, Networks, Patents.

1. Introduction

The spatial dimension of knowledge-driven innovation is a central theme in both the sectoral systems of innovation and knowledge ecosystems literatures (Breschi et al, 2000; Ernst, 2005; Sorenson and Rivkin, 2006; Balland and Rigby, 2017). Within these literatures, knowledge based complexity (KBC) – defined as the integration and combination of diverse scientific and technological fields across a range of activities, such as R&D, design, engineering, and production – has been shown to be important in explaining technological change and industrial dynamics in the automotive industry (Marsili, 2001; Oltra and Saint Jean, 2009) as well as increasing the propensity to enter into technological alliances in the pharmaceutical industry (Krafft et al, 2014).

The debate on the impact of KBC on spatial patterns, however, has been marked by two important, but divergent, accounts of issues such how knowledge is dynamically transferred across space, how system members identify relevant knowledge in various places or domains, and the extent to which they rely on local versus distant sources (Scaringella and Radziwon, 2017). In particular, Breschi and Malerba (1997) argue that innovative activities are more likely to be spatially concentrated when sectoral knowledge bases are tacit, complex and integrated. Similarly, Breschi (2000) suggests that spatial concentration is more likely in conditions of high technological opportunities, appropriability and cumulativeness.

In contrast, Ernst (2005) found for the chip design industry that design-related activities were spatially decentralized despite increasing cognitive and organizational complexity and when knowledge was modular. Moreover, Saxenian (2011) argues that even tacit and complex knowledge can be transferred via transnational technical communities and innovation networks, leading to the formation of technological capacity in novel places.

This aim of this article is to provide longitudinal empirical evidence on such competing claims about the relationship between KBC and spatial innovation patterns, thereby helping to resolve if, and under what conditions, spatially concentrated or dispersed innovation occurs.

Although complexity has been interpreted in different ways by authors such Pavitt (1999) Ernst (2005), Sorenson (2005) and Hidalgo and Hausmann (2009), we define complexity in relation to technological systems and the evolution of a sectoral system's knowledge bases. From a systemic perspective, we argue that complexity has two main characteristics: (i) the number of different elements making up the system, and (ii) the number and strength of the interdependencies among its different elements. We refer to these as (i) technological variety, and (ii) (systemic) complexity.

Subsequently, we ask if *as knowledge base complexity increases, a greater degree of spatial concentration of innovative activities is needed to manage a diverse knowledge base*. To assess this question, we focus on the upstream petroleum industry over a forty year period (1970-2010). This is valuable because the industry has experienced a significant acceleration in innovative activities, the development of new oilfields in new geographies, and competition between new entrants and incumbents over these forty years. Our data are rich in that we have information on patents and patent co-occurrences. This allows us to construct quantitative indexes of the variety, complexity and decomposability of the knowledge base, and to map the changing distribution of innovative activities amongst petroleum producing countries and multinational corporations (MNCs).

We make three empirical contributions to the debate about the relationship between spatial innovation patterns and KBC. First, we find a correlation between the dynamics of KBC and changes in the concentration of spatial innovative activities on a national scale can be observed, provided that a distinction is made between knowledge base variety and systemic complexity. Key to this is that we also show that, starting in 1986, an increase in KBC was accompanied by a rising share of inventions owned by multinationals but not invented in the country where the bulk of their innovative activities was conducted. And consistent with this, we argue that, during the same period, integrated service companies (ISCs) emerged as 'system integrators' (Brusoni et al., 2001) and their share of patenting increased gradually relative to that of integrated oil companies (IOCs). Such results are valuable as they show under which conditions the complexity of this industry's knowledge base shapes its geography of innovation.

In summary, the overall contribution of this paper is to provide a nuanced account of the relationship between KBC and the spatial concentration (or dispersal) of innovation. A practical implication is that we provide evidence that some multinationals – especially ISCs - played a driving role within the industry knowledge network and although they may operate globally, their core innovative activities still remain in advanced countries. This is consistent with Cantwell's (1995; 2009) theory of the globalisation of technological development.

The article proceeds by providing a brief overview of differing accounts of the relationship between KBC and the spatial concentration of innovation and then formulating our central research proposition in Section 2. Section 3 focuses on data collection and methodological issues. In Section 4 we present the results for the dynamics of KBC in upstream petroleum. In Section 5, we examine our findings for the patterns of international geography of innovation. Section 6 our results on the emergence of new industry players is presented. Section 7 summarizes our findings, and concludes.

2. KBC and Spatial Patterns of Innovation

In this section, we first clarify how we define complexity. We then outline two contrasting perspectives on the relationship between KBC and spatial patterns of innovation and proceed to examine more granular contributions, prior to developing our key research question.

Knowledge Base Complexity

One key feature that emerges from the extant literature is that complexity can be defined in different ways. Pavitt (1999) links it with cognitive and organizational complexity, whilst Sorenson (2005) equates complexity to highly interacting knowledge components. Meanwhile, Hidalgo and Hausmann (2009) conceive a knowledge base as being complex if it relies on a wide range of technological classes a few places specialize in, and such specializations occur in the same places.

In contrast, Ernst (2005) defines complexity as an increasing range of specialized knowledge arising from the decomposable knowledge base of an industry. Yayavaram and Ahuja (2008), though, argue that a firm's knowledge base reflects its 'best guesses' on the interdependencies between elements of the knowledge system within which it operates. Innovation originates from the matching of 'deep knowledge born out of specialization and variety generated through broad exploration' (p. 340) and requires effective integrative mechanisms (e.g. knowledge integrators). Accordingly, when a firm's knowledge base is fully modular and decomposable, its capacity to identify synergies and learn across knowledge fields may diminish. However, if a knowledge base is highly integrated, firms might find it more difficult to deviate from existing trajectories by decomposing and recombining elements of the knowledge base in novel ways.

Although there are a range of ways that complexity can be defined, from a systemic perspective, the complexity of the system has two main characteristics: (i) the number of different elements making up the system, and (ii) the number and strength of the interdependencies among its different elements. The latter point implies that a complex system has a hierarchical structure of components with multiple, dense interactions, and cannot be easily decomposed (Singh, 1997). Hence, we refer to (i) as technological variety, and (ii) as (systemic) complexity.

The spatial basis of KBC

Patel and Pavitt's (1991) seminal argument on the 'non-globalization' of innovative activities is that geographical concentration enables companies to manage complexity in innovation processes. Later, Pavitt (1999) emphasised that complexity allowed for the mobilization of a wide range of specialized competences since these encourage spatial concentration and facilitate links between the elements of a knowledge system and learning processes.

Breschi (2000) builds on these insights by arguing if the knowledge base is tacit, complex, and part of a larger system, there is a greater need for it to be spatially concentrated. Sorenson (2005) also finds that complexity leads to a higher spatial concentration of industries since it constrains knowledge flows which is a pattern that Leamer and Storper (2014) anticipated as being likely to continue despite the further diffusion of information and communication technologies. Using an index developed by Hidalgo and Hausmann (2009), Balland and Rigby

(2017) further showed that in the US complex patents are less likely to be cited by patents generated in different metropolitan areas.

In contrast, in Ernst's (2005) study of the chip design industry, design-related activities were found to be spatially decentralized despite increasing complexity. Ernst observed that complex knowledge can be transferred between distant organisations because cognitive proximity can be achieved through global innovation networks. However, this was only possible because there was a degree of modularity in the knowledge base that facilitates the outsourcing of specialized work to distant suppliers. If the industry's KBC is decomposable into relatively independent components, specialized agents could innovate without necessarily having to access to other complementary pieces of knowledge. This is because market and semi-market decentralized systems serve as coordination functions and, counter to Pavitt's (1999) argument, vertically integrated structures are not necessary for knowledge exchange at distance. Ernst (2005), though, acknowledges that there are limits to the convergence between technological and market modularity. Notwithstanding the role played by effective 'virtual coordination', complexity can increase, and cognitive hurdles can arise because of technological diversification and geographical dispersal.

Other contributions to understanding KBC

Alongside these contributions, other important studies have pointed out that the integration of modular knowledge often requires integrative mechanisms or, as Brusoni et al. (2001) suggest, "system integrators" that "lead and coordinate from a technological and organizational viewpoint" (p. 613). These are important because they provide a set of complementary activities and/or working units specialized in different technical domains.

Coordination can also lead to the spatial concentration of innovative activities to manage high complexity. Carrincazeaux et al. (2001) argue that as combinatorial (the assembly of diverse knowledge components) and technological (the frequency with which new knowledge is implemented) complexity increases, geographic proximity is required to coordinate activities within the same firm or across different ones. Such a proximity is not necessarily geographical, as both organisational and cognitive proximity can play an equally significant role (Amin and Cohendet, 2004; 2005). Balland et al. (2015) concur that organisational and cognitive proximity can serve a key function in facilitating the interaction of learning and innovation.

An important caveat to these findings is that the way in which the interaction between complexity and proximity in coordination shapes innovation processes varies significantly from one industry to another (Carrincazeaux et al., 2001; Rycroft 2007). For instance, Cantwell and Mudambi (2011) investigate the competence creating activities of MNCs and argue that in dealing with a varied knowledge base MNCs rely on global innovation networks only in industries with a highly concentrated structure.

Assessing the relationship between KBC and the spatial concentration of innovation

Core to our argument is that as the spatial concentration of an industry is likely to be impacted by (i) technological variety, (ii) (systemic) complexity, and (iii) decomposability of its knowledge base. Variety increases as an increasing range of knowledge fields contribute to its evolution (Wang and Von Tunzelmann, 2000). If this happens without multiple and dense interactions between the different knowledge fields, the knowledge base becomes decomposable (Antonelli, 2011). If so, this implies, following on from Pavitt (1999), that when an industry's expanding knowledge base is characterised by high variety and low complexity, new innovators could exploit emerging technological opportunities regardless of their location.

Antonelli (2011), however, argues that if the degree of interdependency increases, changes in one component of the knowledge system are likely to have radical and unpredictable impacts on other system components. Consequently, having access to systemic or architectural knowledge is necessary because coping with a more complex, less decomposable, and varied knowledge base is more challenging for spatially distant agents, particularly in the absence of effective integrative mechanisms. In this case, it can be very difficult for distant players to cooperate and innovate without integrative mechanisms or recipients with high absorptive capacity (Sorenson, 2005; Sorenson and Rivkin, 2006; Herstad et al 2014). Cantwell (1995), for example, notes that innovation may happen at various locations, but multi-technology companies can resort to complex organisational structures to coordinate them on a global scale. Bridge and Wood (2005) advance a similar argument in the context of the petroleum industry, adding that the relative importance of distant versus local sources will depend on the intrinsic features of the knowledge base.

Based on the extant literature, therefore, our central research question is: *as knowledge complexity increase and decomposability decreases, is a greater spatial concentration of innovation needed to manage a diverse knowledge base?*

3. Method and Data Collection

This section begins by briefly outlining the upstream segment of the petroleum industry. We then outline our data, focusing on three areas of interest: the indexes used to render knowledge base dynamics, how we assess the spatial concentration of innovation, and how we study industry structural transformations. Each of these areas of enquiry are taken up in later sections.

3.1 The Upstream Segment of the Petroleum Industry

The upstream segment of the petroleum industry has a relatively long and complex value chain; from the exploration and production of crude oil, to transportation, refining, and retail. It focuses on searching for potential underground or underwater crude oil and natural gas fields, drilling of exploratory wells, drilling and operating existing wells, bringing the crude oil and/or raw natural gas to the surface, and storing it. It also involves the business activities which complement and feed into these core activities. Suppliers and service companies include those that build equipment and offer specialised services, such as firms for marine, sub-sea, and sophisticated geo-activities. Historically, the upstream petroleum industry has exemplified several phases of transformation and reconfiguration, providing a very relevant setting for the analysis of dynamics of technological regimes and spatial patterns of innovation. Bridge (2008) regards it as a complex ecology, in which 'exploration and production activities are best conceptualized as hollow or networked projects' (p. 400), and in which the spatiality of the global production network is a complex interplay between the geographical localization of knowledge-intensive activities and the concurrent delocalization of extractive ones.

3.2 Constructing indexes to measure variety, complexity and decomposability

To derive our three indexes for the dynamics of KBC (section 4), we use patent data obtained from the Derwent Innovation Index. This database classifies all upstream petroleum industry patents in class H01. H01 covers exploration, drilling, well services, stimulations, production, and its sub-segments in upstream petroleum. Derwent uses the international patent classification (IPC) and also provides further information regarding the functions and technical fields of each invention. We specify the IPC, the country of assignees, and the country of inventors, to all patent records drawn from H01. Each classification system constitutes a hierarchical categorization where the higher levels (e.g. 4-digit) are disaggregated into more detailed categories (e.g. 7-digit level). Table 1 shows the number of IPC classes at each level and the share of patents assigned to each class. Our data are for the period from 1970 to 2005. This is because, although our dataset extends to 2010, we experience a truncation bias due to delayed information for patents granted after 2005. Therefore, we can only present reliable results up to 2005.

Table 1: Distribution of patents within IPC classes at different levels

In Tables 2 to 5, we show the top 20 classes/subclasses at the 1, 3, 4 and 7-digit levels, ranked according to their share and the number of patents in each category. When comparing these tables, the distribution of patents across technological classes are highly skewed (e.g. at the 4-digit level almost 32% of all inventions are recorded in E21B (drilling technologies)). Hence, since capturing the dynamics of KBC requires higher disaggregation, we use the 7-digit level, where only 7.8% of patents are included in class E21B-043 (Table 5). Furthermore, we avoid multiple counting of the same invention registered in more than one country by using Derwent International Patent Families (IPFs) records and grouping similar inventions registered in different territories.

Tables 2-5: top 20 classes, 1,2,3,4 and 7-digit

Index of Variety

We focus on the dynamics of variety as this is considered an important aspect of the sectoral knowledge base (Wang and Tunzelmann, 2000; Boschma and Iammarino, 2009), which provides a basis for inter-sectoral comparisons. Following Krafft et al.'s (2011) work on the dynamics of sectoral knowledge bases, we employ the Entropy Index (see Appendix 1) to measure variety. This index measures the degree of disorder or randomness in a distribution, assigning higher values where distribution is more balanced.

Index of Complexity: Weighted Average Degree of Centrality

A number of issues have to be accounted for in developing an index of complexity. One main concern of scholars writing on complexity is the volume of interdependencies and degree of interaction between elements of a system (Wang and von Tunzelmann, 2000; Antonelli, 2011). Here connection between technological classes is established through their joint utilization (Krafft et al 2011). Other authors use patent data to develop alternative indicators of complexity, for instance to measure the degree of diversification of a country's (Ivanova et al 2017) or a region's (Balland and Rigby 2017) economic system.

Knowledge complexity is also important when opportunities to produce new knowledge are dependent on the identification and amalgamation of complementary components. Knowledge indivisibility is the result of a process whereby systemic knowledge performs new functions that cannot be served by individual components of knowledge. In sectors with high levels of such complexity, innovation and production activities depend on (i) access to and control of varied knowledge, and (ii) integrative coordination capacity. Successful innovation is unlikely to happen without an understanding of the compatibilities among different but complementary technologies. The cause of this complexity is often systemic innovation (Chesbrough and Teece, 1996, Maleki et al. 2016).

Our proxies for measuring complexity use the network of links and interactions between different elements of the knowledge base, and capture the recombinant nature of knowledge and its endogenous complexity. Hence, the knowledge base has a correlational structure comprising of nodes and the links between them (Saviotti, 2011) with nodes representing technology classes and links the relationships between technologies, which connect the nodes together. As such, dynamics of complexity result from changes in the pattern and strength of linkages or interactions between the nodes. We employ Social Network Analysis (SNA) to examine the dynamics of systemic KBC in upstream petroleum, using the concept of weighted average degree of network centrality (WADC) (see Appendix 2). The use of WADC has been shown to be appropriate to understand the dynamics of systemic KBC in different contexts. Saviotti et al (2011) used it to assess the evolution of patent networks whilst Nam and Barnett (2011) use it to study the process of globalization of technological development. Furthermore, Hu et al (2017) employ it for examining the position of countries within global innovation networks and He and Fallah (2009) draw on it to understand the effect of inventor networks on the transformation of technical systems and industrial clusters.

For our purposes, we consider that when the speed of formation of new nodes outweighs that of links, the network becomes less connected (WADC decreases) and complexity is expected to decrease. In contrast, when the formation of new links is quicker than that of new nodes within the knowledge network, network connectivity increases, signalling the rise of complexity.

Index of Decomposability

Knowledge base decomposability reflects the degree of integration and interdependence between knowledge domains or clusters. Yayavaram and Ahuja's (2008) decomposability index relies on dyadic relationships within and between clusters of technological classes, and employs a modified weighted clustering coefficient which distinguishes between strong and weak linkages. They use it to provide a useful perspective into a firm's ability to search for and recombine complementary knowledge elements. We adapt and use it to analyse the evolution of the industry's knowledge base.

High decomposability is accompanied by raised modularity and a specialization in knowledge search and utilisation, which does not require geographic concentration (Ernst, 2005). In contrast, low decomposability requires effective mechanisms for knowledge integration and, at industry-level, the rise of organisational entities such as system integrators that perform such a function. Over time, changes in the network of interdependencies at industry-level affect a firm's ability to recombine knowledge components (Yayavaram and Wei-Ru Chen, 2015).

3.3 Measuring Spatial Patterns of Innovation

Whilst it is widely acknowledged that production activities in upstream petroleum tend to agglomerate in proximity to certain extraction sites (Bridge 2008), we follow Motoyana et al (2014) and Liu and Sun (2009) and use patent data and a corrected version of the Herfindahl Index to illustrate the trend of spatial distribution (concentration vs dispersal) of innovative activities. Furthermore, we adopt the method developed by Danguy (2017) to represent the shifts in the spatial patterns of innovation, in terms of foreign ownership of domestic innovation (patents which are invented in a country, but assigned to foreign companies operating there) versus that of locally-owned (patents which are invented in a country, and also owned by companies with the most inventions in that country) and co-owned patents (patents which are invented in a country, but co-owned by both local and foreign companies).

Although our analysis focuses on the spatial patterns of national patent assignation, we also differentiate between the loci of innovation generation (inventor address) and those of innovation ownership (assignee address)[i]. This is important because over 1970-2010, the opening of new oil fields led to an increased dispersion of extractive activities and, concurrently, MNCs continuing to own a large share of the patents. Dependent on changes in the intensity of KBC, this may lead them to have adopted different strategies to manage their knowledge bases across space. Moreover, because it can be difficult to define the nationality of MNCs operating in upstream petroleum - particularly where there are many foreign affiliates and subsidiaries - we also distinguish between an assignee's address as reported in patent documents (the 'inventor's country') and the location(s) where the bulk of an MNC's innovative activities takes place. We call the latter an 'assignee's main invention country'.

As a final step, the findings on the dynamics of KBC and spatial patterns of innovation are combined and interpreted by considering the structural transformation through which the industry adapted to an increasingly complex and integrated knowledge base.

3.4 Distinguishing between industry players

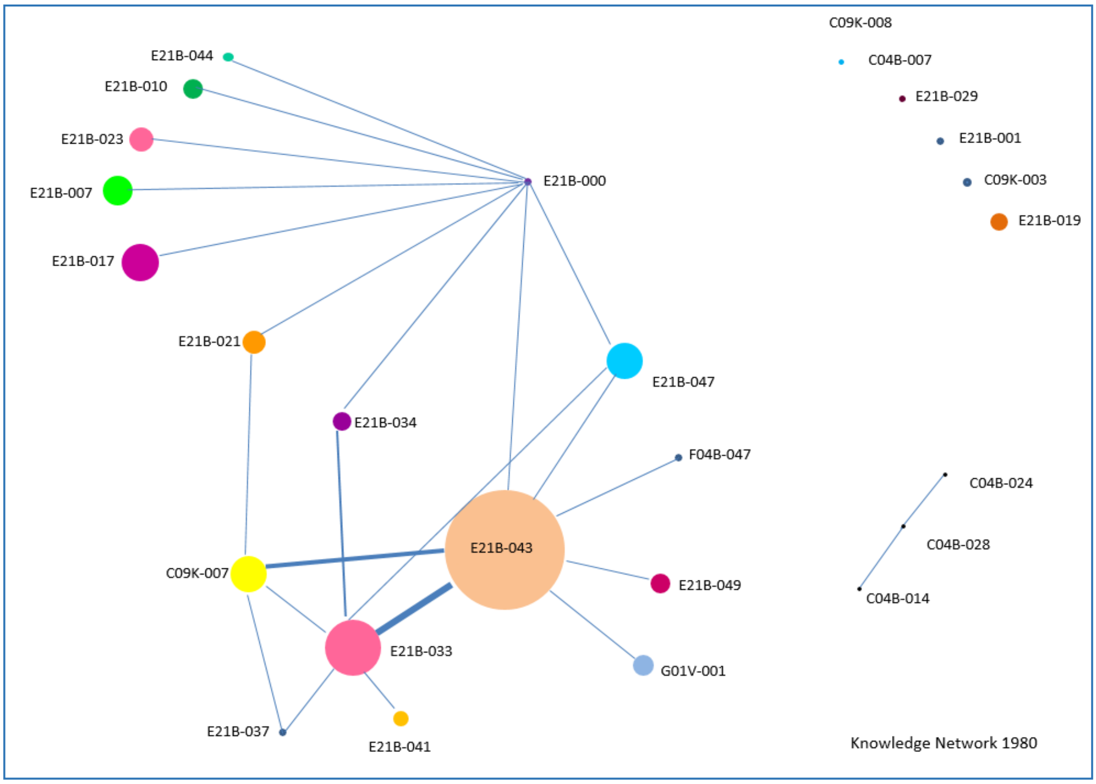
Our dataset allows us to distinguish between three main types of industry players: IOCs, ISCs, and other specialized supply and service companies (SSCs). Understanding how these three distinct types of companies performed over the evolution of KBC is important since it helps to understand spatial patterns of innovation. Thus, we build two indexes to assess the trend of a firm's knowledge stock and relative share of patents over time, as well as a Normalized Average Diversity index to represent the degree of diversity in its knowledge base.

4. Results: Dynamics of Knowledge Base Complexity

In this section, we measure and analyse dynamics of KBC by distinguishing between variety, complexity and decomposability. These three dimension offer complementary insights into how the complex knowledge base of an industry evolves over time and expands across geographical spaces (Breschi, 2000; Sorenson, 2005; Ernst, 2005) and technological domains (Pavitt, 1999; Yayavaram and Ahuja, 2008; Carrincazeaux and Coris, 2011).

4.1 Dynamics of variety and complexity in upstream petroleum

Figure 1 shows changes in the knowledge network structure from 1980s to 2005 for core nodes and linkages. Considering knowledge base as a complex system represented by a knowledge network (Saviotti, 2011), variety corresponds to the patterns of the nodes (expansion or contraction in number), while systemic complexity shows the links and connectivity of the network. Only core nodes and linkages are considered, which allows for a clearer graphical representation (Appendix 3 shows the pattern of emergence of some core technologies).



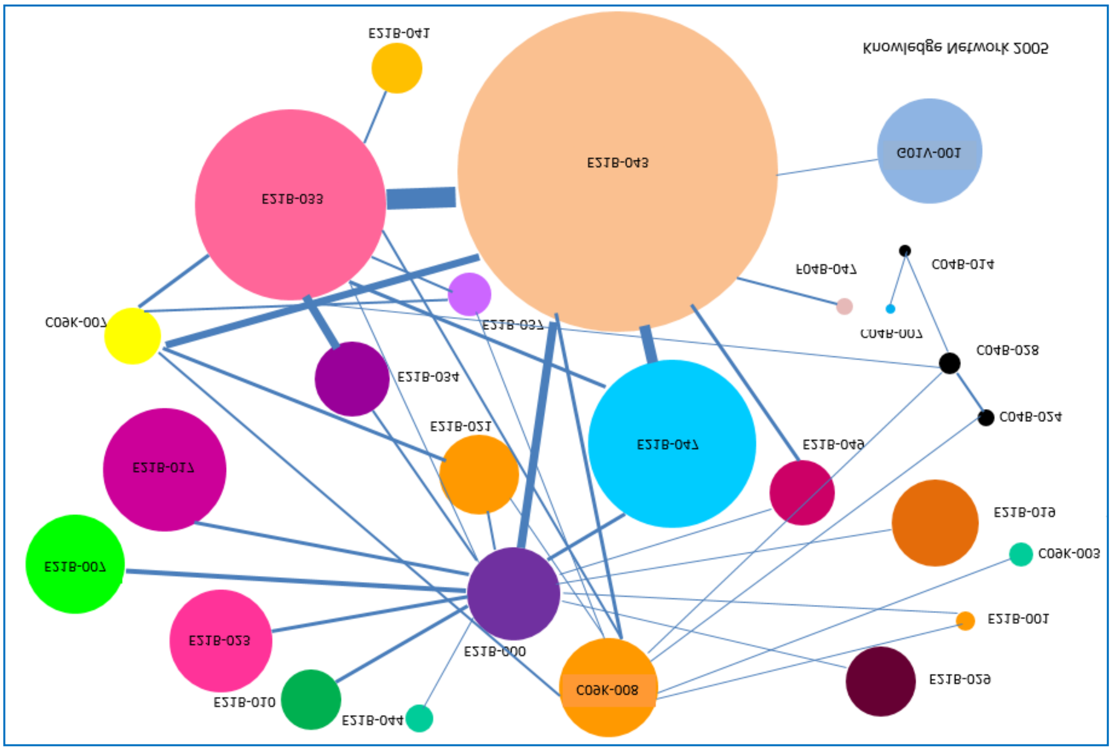


Figure 1: The Industry's knowledge network in 1980 and 2005.

Figure 1 illustrates that the industry's complexity increased due to the integration of core nodes within its knowledge system (e.g. technology classes C04B-4, 24, 28), as well as increased intensity of the links between different nodes (e.g. E21B-33 & E21B-43; C09K-008; E21B-33). The dynamics of variety and complexity are presented in Figure 2. The two seem related, yet move in opposite directions, with a transitional phase in the mid-1980s. Turning first to variety, it initially presents an upward trend. Achieving its peak in 1983, it then begins a downward trend through the late 1980s. In contrast, complexity has an overall declining trend until 1986, then turns upwards in the early 1990s. The period up to 1985 is characterised by high instability and uncertainty due to increasing technological variety. Historically, in this phase the industry experienced rapid technological progress as innovative solutions (like 3-D seismic and horizontal drilling) were first introduced (Neal et al., 2007). Baaji et al (2011) refer to a 'reserves access' phase that coincided with an increase in oil prices as well as a worldwide wave of nationalization of oil reserves in many countries, pushing MNCs to invest in technological development to explore new reservoirs. Not only did new technological classes emerge and add to the knowledge range of the industry, but the industry also moved towards a more equal distribution of innovation within different technological classes. This boosted technological variety, moving the sector towards higher variety. Meanwhile, complexity decreased as the result of a higher rate of creation of new nodes (or technological classes) compared with new links between new and existing nodes.

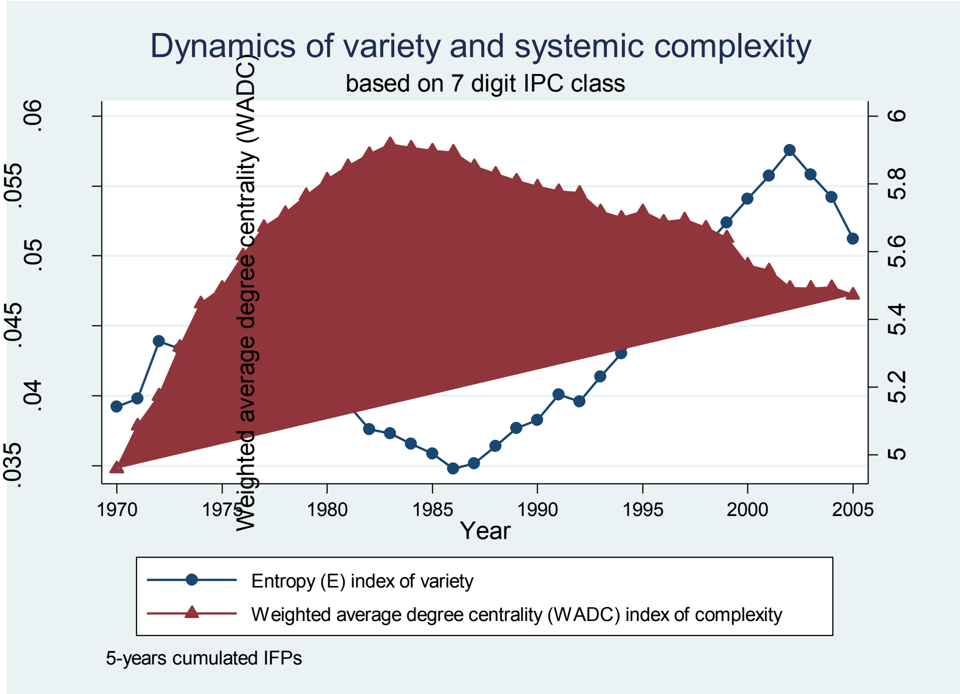


Figure 2: Dynamics of variety and complexity

Figure 3 shows that the patterns of knowledge base decomposability (blue line) and integration (red line). The knowledge integration trend mirrors that of complexity shown in Figure 2, with the notable addition being that, up until 1986, declining KBC coincided with an increasing trend of decomposability.

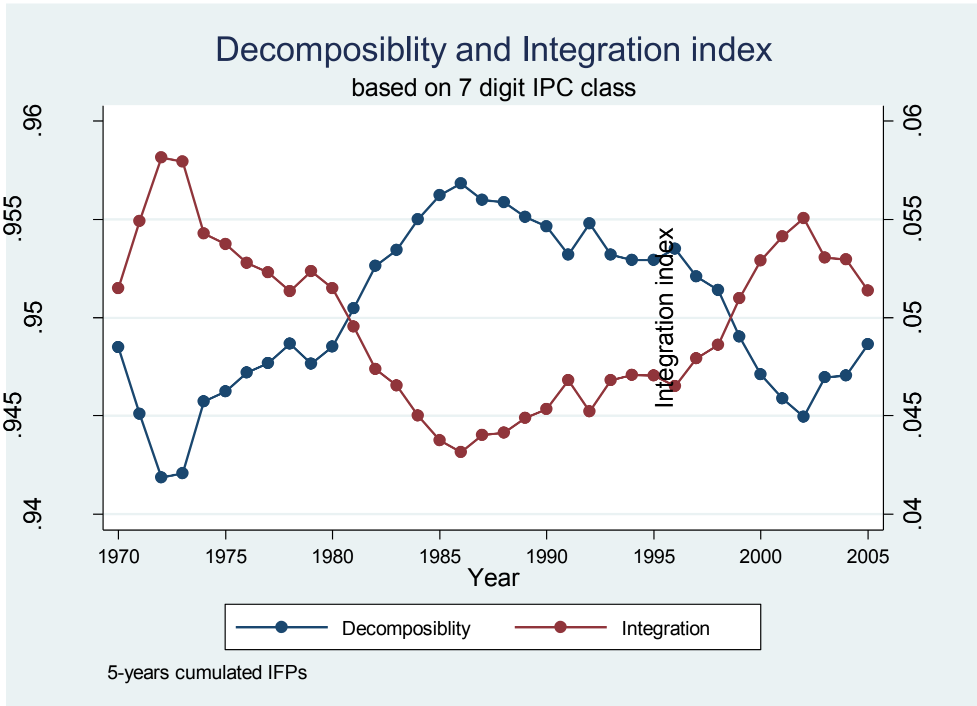


Figure 3 – Trend of Knowledge Base Decomposability

The direction of complexity reversed around 1986, implying a rise in connectivity across the knowledge network (Figure 2). In this new phase, increasing complexity overlaps with an upward trend of knowledge integration (Figure 3). Complementarity among new technological fields explored in the 1970s and 1980s helps to explain the shifting pattern. The rate of creation of new links overtook the rate of emergence of new nodes, because the industry's incumbents already knew the most promising fields explored during the previous period. The emergence of new technological fields did not stop, but their relative size became negligible compared to established technological fields.

This relates to three wider events: 1) Saudi Arabia's 1986 decision to increase the amount of oil to be released onto the international markets which drove prices down significantly in the late 1980s; 2) the sharp increase in Russian productive capacity followed the collapse of the Soviet Union which, again, contributed to keeping prices low throughout the 1990s; and 3) the fact that public policy approaches to natural resources management began to shift towards the adoption of more liberal policy models, within which the attraction of foreign investment tends to prevail over rent capture from royalties or taxation (Mommer, 2002).

Consequently, in this phase of 'efficiency focus' (low prices and liberal public policies), the strategic imperative for many MNCs shifted towards reducing the upstream cost of exploiting existing reservoirs, pausing technological development in deep waters, and concentrating R&D investments on improving the productivity of existing reservoirs (Baaji et al, 2011). The main emphasis of the industry's innovation efforts was on "incremental changes and further development of earlier exploratory work primarily to reduce costs and enhance the feasibility of projects within the existing water depth boundary" (Dantas and Bell 2011, p. 1582).

Following Krafft et al (2011; 2014), we argue that in this 'efficiency focus' phase the search strategies of industry players also became more organized and focused on exploitation of the most productive technological areas rather than exploration of new fields. This meant that innovation increasingly occurred within or at the interfaces of technological classes which proved promising and fruitful, with a lower dispersion of R&D investment across fields.

Around the mid-1990s, though, the industry started to refocus its agenda on finding new and more complex reserves in (at times) harsher environments. Indeed, the prolonged regime of low prices (which continued until 2003) meant easily accessible reservoirs were being progressively exhausted. Such a strategic and technological imperative demanded innovative solutions around upstream operations through the combination of various technologies

(Hassani et al, 2017). In return, investments in technological development promised important returns in terms of scope economies, and in the shape of 'highly specialized design and engineering capabilities to develop technological solutions capable of addressing the heterogeneity of exploration conditions and reservoir types' (Bridge 2008, p. 407). For example, downhole steerable motors controllable from the surface were introduced and used alongside measurements-while-drilling techniques, supporting the diffusion of directional drilling (Neal et al., 2007). In addition, digital-oilfield technology became possible through the combination of mathematics and data technology with petroleum science and know-how.

Overall, the geopolitical, economic and technological trends that began to shape the industry's evolution in 1986 intersected with an increase in systemic KBC, rather than more variety (or entropy), demanding a full understanding of interdependencies across distinct technological classes (Krafft et al., 2011). It also became harder to decompose an expanding knowledge base into single or clusters of technological classes. The knowledge base, therefore, moved from the accumulation of knowledge in existing domains or the simple addition of new technical domains to one focused on the interactions and the recombination of existing and innovative technologies (Maleki et al., 2016). Such conditions are more to the advantage of agents that possess or have access to an array of knowledge components. Within the knowledge network, those who occupy central positions are ideally placed to reconnect the expanding number of knowledge components, and therefore generate new knowledge (Antonelli, 2003).

Meanwhile, from the late 1980s non-state-owned IOCs began to outsource complex upstream operations, to manage the expansion in the search space and achieve economies of scope by turning high internal fixed costs into variable ones (Bridge, 2008). This process led to the emergence of oilfield ISCs – such as *Schlumberger Ltd* or *Halliburton Company* - that were able to manage an increasing range of specialized tools and subcontractors at the interfaces of various technical fields (Chafcouloff and Michel, 1995; Barreau, 2002; Dale et al., 2014).

In Figure 2, decline in complexity that starts in 2003 resembles a point of technological discontinuity whereby connectivity within the knowledge network declines. Figure 3 also shows a change in the direction of the decomposability/integration index, which after two decades begins to decline. The industry seemed at the outset of new technological cycle. Unfortunately, due to a truncation bias we can only present reliable results up to 2005, which does not allow any definitive conclusion to be drawn.

5. Results: Spatial Patterns of innovation in upstream petroleum

This section examines the changes in the spatial concentration (or dispersal) of innovation that occurred across different economies. We construct two measures using a dual data source to investigate shifts in the international geography of innovation over the 1970-2005 period. These measures are the extension of similar proxies used in the analysis of innovation patterns by Breschi et al. (2000) and Maleki et al. (2016), extended to geographical domains.

At the start, it is important to explain how geographical data is used for international comparison. The inventor's country (IC) in the patent document is often seen as the most relevant proxy for geographical location (OECD, 2009). Nonetheless, this assumption can be misleading because this data does not distinguish between innovations made by domestic or foreign companies located in a country. In some cases, big MNCs assign some of their inventions to certain subsidiaries and/or relocate part of their R&D operations to follow market expansion strategies, benefit from tax incentives, or take advantage of favourable cost conditions. This may involve limited collaboration with and/or knowledge spillovers to local companies, and limited impact on local innovation capacities.

However, we distinguish between the location of inventors and assignees. This allows us to separate those who own or control the innovation from the original inventor(s), and identify their locations. Moreover, since inventive activities of foreign affiliates (in other countries) are sometimes attributed to a host country if the affiliates are registered locally, we introduce the concept of assignee's main invention country (AMIC). It assumes a patent can be assigned to a specific location only if a certain proportion[ii] of an assignee's inventions are also registered there. In contrast, patents are re-assigned to a different address if an organisation does not conduct any (or only minimal) innovation in the country to which they are formally assigned.

First, in Figure 4 we present the dynamics of international spatial concentration of innovation across different economies, based on the corrected version of Herfindahl index of concentration using both IC and AMIC sources. The advantage of this corrected version is that it controls for small sample bias (Hall, 2000). In addition, the number of contributing countries (N) is presented on the right axis. It shows that the number of countries both in terms of IC and AMIC of innovation has increased over time. Except in the early period up to 1977, the number of owner countries (AMIC) has always been lower than the number of countries where innovative activities are located. Moreover, the gap has increased for most of the observed period, particularly after the mid-1980s. This signals that the pace at which new innovators arise in new countries is more intense than the trend of emergence of countries that already had indigenous innovators.

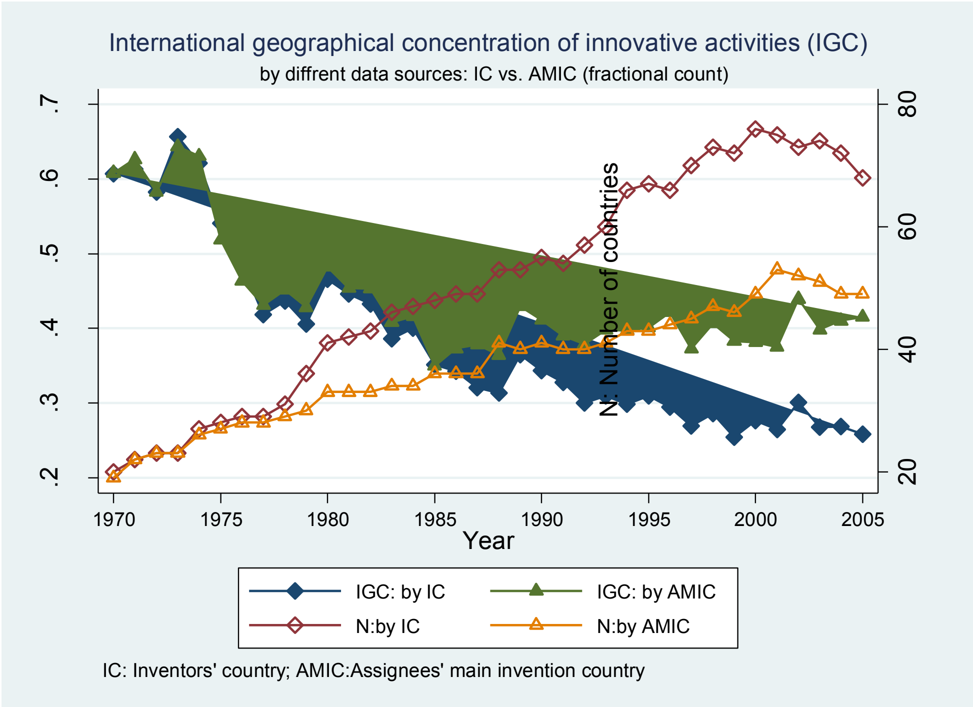


Figure 4: International spatial concentration of innovative activities

A comparative analysis of spatial concentration is even more informative. Comparing IC and AMIC shows that, until 1986, concentration based on both sources experienced a non-divergent downward trend. This means that new sources of innovation emerged in new countries where most innovations were also owned by local agents. Thus, the concentration index according to both IC and AMIC followed similar patterns.

However, they began to diverge considerably around 1986, when the overall trend of spatial concentration based on AMIC began a gradual upward trend. Concentration per IC continued its downward trend, though at a slower rate after 1986. This indicates that the physical location of innovation (i.e. the inventors) became increasingly dispersed. This seems in line with a more general trend towards globalization of technological development (Nam and Barrett, 2011).

The geography of innovation became more concentrated in terms of 'assignee countries' between 1986 and 2003. Many technologies developed within the upstream petroleum industry were owned by multi-locational firms with established R&D operations in global centres of expertise (e.g. Houston for exploration and production activities), although geographical 'extensification' of extraction activities led to the contemporaneous dispersal of a considerable proportion of inventive activities (Bridge and Wood, 2005; Bridge, 2008). Around the same period, as the earlier Figures 1, 2 and 3 show, complexity began to increase with coordination and integration of knowledge bases over large distances becoming more challenging.

Second, in Figure 5 we employ Dunguy's (2017) method to illustrate the trend of innovation ownership (local, foreign, or shared). When we compare Figure 3 with the KBC trends shown in Figures 2 and 3 and the pattern of concentration of innovative activities in Figure 4, we observe that increasing variety up to the mid-1980s coincides with increasing geographical dispersal and the share of patents assigned to foreign companies remains limited. This complexity is partly due to the proliferation of different "physiographic and socio-political environments" in the project portfolio of MNCs, which entailed the emergence of "location-specific knowledge requirements" (Bridge and Wood, 2005, p. 206). This in turn explains why our two measures of spatial concentration (IC; AMIC) present a declining trend (Figure 4).

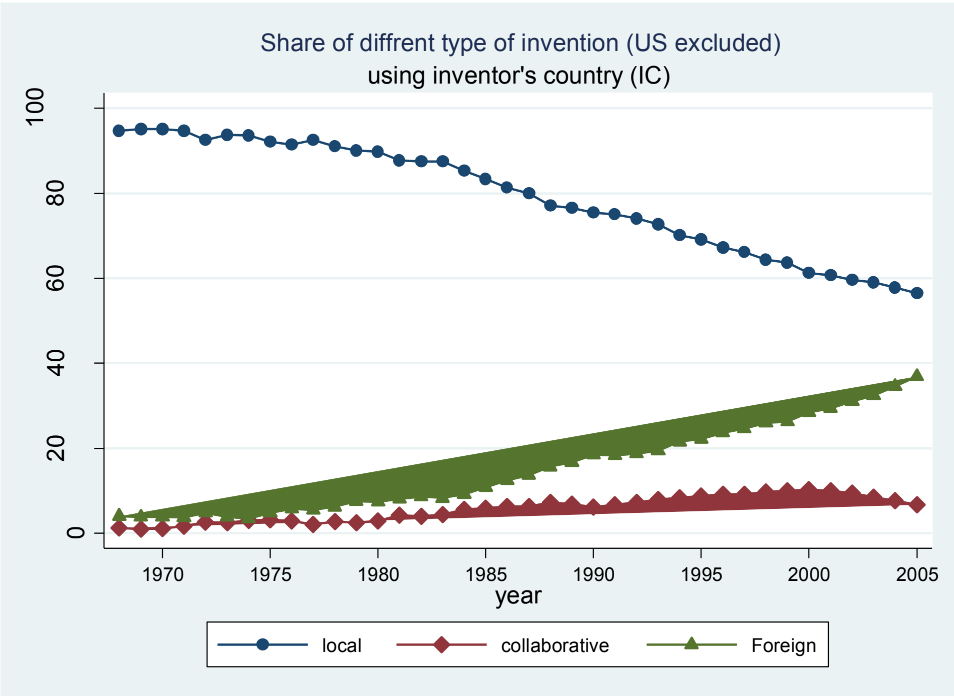


Figure 5: Share of diverse types of invention per each country's ownership

After the mid-1980s, however, Figure 5 also shows a constant increase in the share of inventions owned by MNCs but not invented in the MNC's country of origin. This confirms that, although innovations were becoming spatially dispersed at a national scale, their ownership was increasingly concentrated. Despite geographical dispersal across clusters of knowledge creation, the cognitive proximities developed by MNCs through their global production networks (Bridge, 2008) appear to have been critical for coping with high KBC and integrating an expanding range of increasingly integrated knowledge components involved in complex projects (Chafcouloff and Michel, 1995; Berggren et al., 2013).

In summary, we show that when variety was initially dominant and decomposability high, companies innovated within specific technological classes without access to knowledge in other parts of the system. This indicates that spatial concentration was not important. However, as higher technological opportunities began to materialise in the mid-1980s (Maleki et al., 2016), the level of complexity and integration among technological classes also increased, requiring an economic organisation of spatially dispersed activities able to facilitate the exchange and coordination of complex knowledge flows over larger geographical distances This change coincided with an initial phase of low prices and ‘efficiency focus’ (Baaji et al, 2011) whereby IOCs focused on the exploitation of existing reservoirs and began to outsource some extraction-related activities and services. By the mid-1990s, the price regime had not changed. However, the search for new sources resumed and the outsourcing trend accelerated forward. Our results show that between 1986 and 2003, while inventors became more geographically dispersed, ownership of their inventions became increasingly concentrated.

6. Results: The emergence and role of System Integrators

Alongside shifting spatial patterns, we consider whether certain adaptations of the industry structure could have been necessary to coordinate innovative activities and facilitate interactive innovation across an expanding space (section 2, 3). To examine the role of different industry players (IOCs, ISCs, SSCs), Figure 6 shows the trend of the (logarithm of) average innovation stock for each these three types of company, alongside their relative share of IPFs in Figure 7.

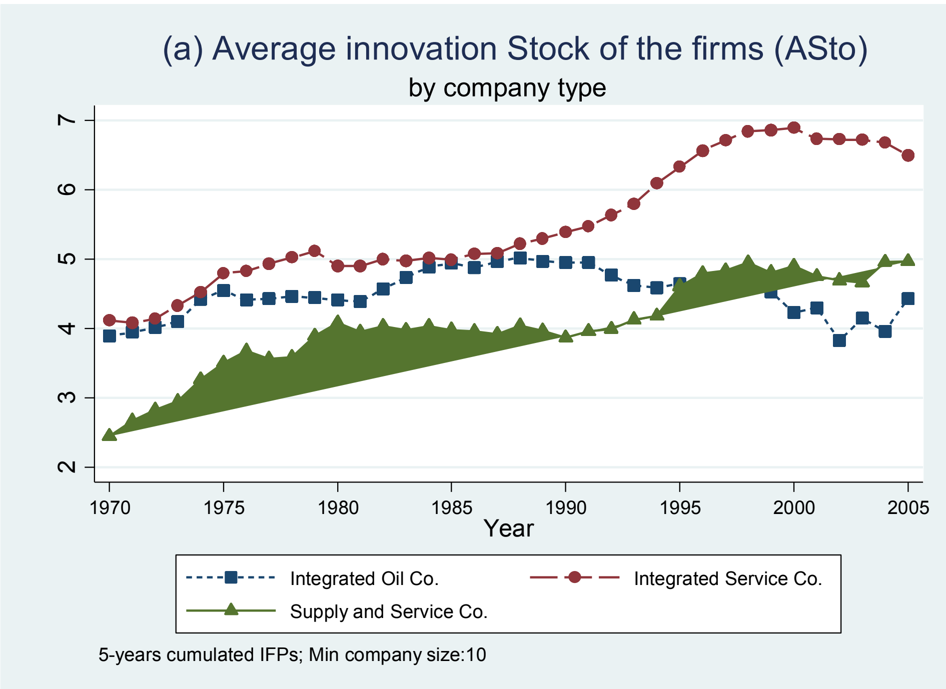


Figure 6: Innovation Trends for IOCs, ISCs, and SSCs (patent stock)

Secondly, we study the innovation strategy of different types of players, to ascertain how they adapted to the dynamics of KBC.

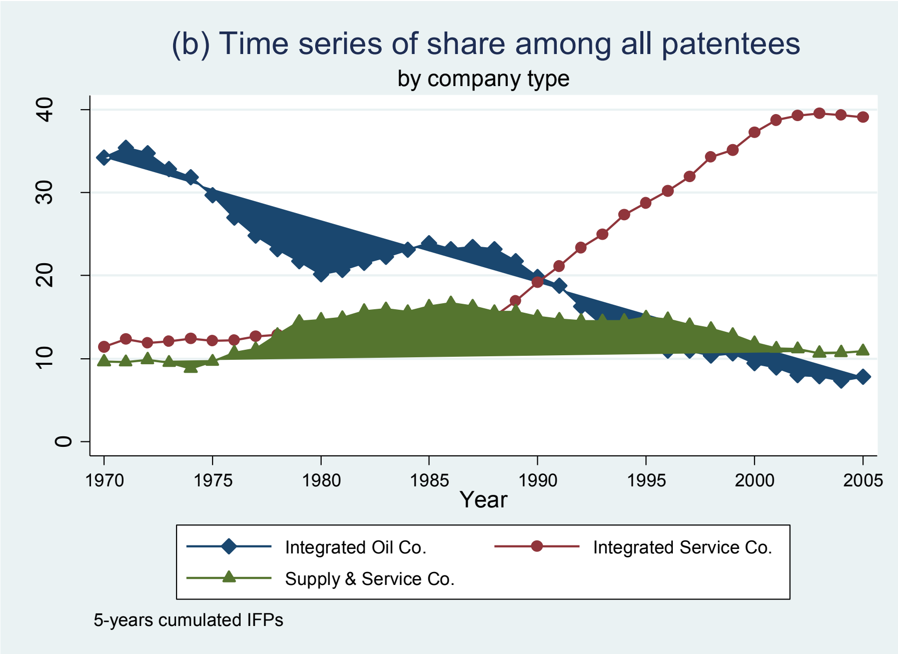


Figure 7: Innovation Trends for IOCs, ISCs, and SSCs (patent share)

We ask if their knowledge base followed a pattern of technological diversification or specialization at different points in time. We use a Normalized Average Diversity (*NADiv*) index to represent the average degree of diversity in the knowledge base for different types of companies at different points in time. The number of 7-digit IPC classes in which companies register patents measures the diversity of their knowledge base. We calculate the average value of this measure for each group of companies, and normalize it using the mean value of diversity over the entire sample in each year of the 1970-2005 period.

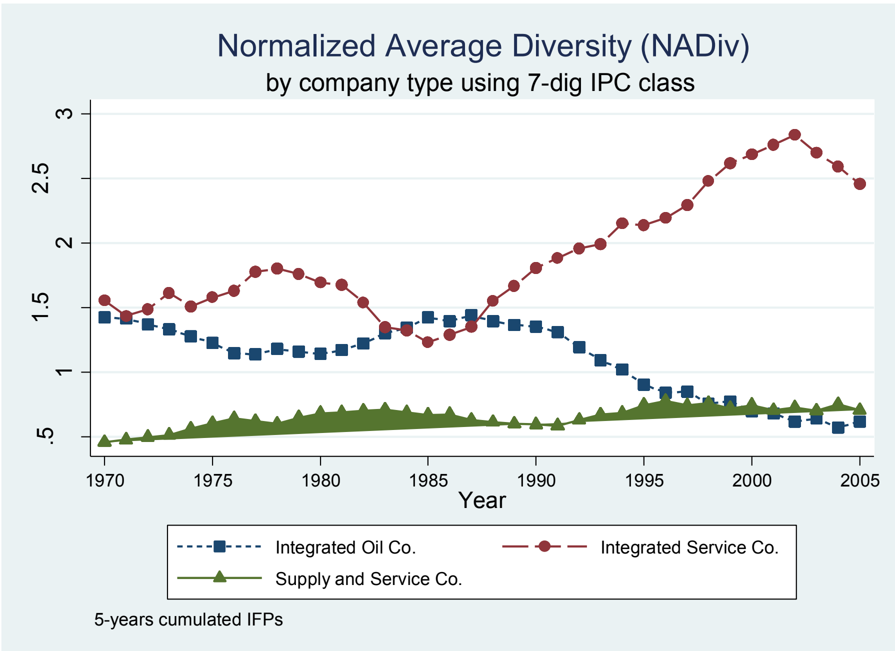


Figure 8: NADiv 1970-2005

Figures 7 and 8 also show that new technological fields were being introduced to the industry knowledge base by all three types of players at a similar pace up until the mid-1980s, while the level of diversity in their respective knowledge bases was not significantly altered. This suggests that technical interdependencies among different domains were not pervasive, and high knowledge integration capacity was not necessary. Markets operated as effective coordination mechanisms to exploit interdependencies.

However, by 1990 the technological pathway of distinct types of companies diverged. In particular, the overall contribution of IOCs to the innovation process declined. Oil projects became larger, more complex, and technologically challenging. Whilst becoming increasingly specialized (*NADVid* decreases in Figure 8), IOCs maintained their system integration role at the top end of the value chain. They invested capital, took equity shares in oilfields, sought returns on such equity positions, managed subsurface geology, and took significant capital risks, in terms of both the reservoir and the price of hydrocarbons (Beyazay-Odemis, 2016).

Around 2003, both the stock and share of patents controlled by IOCs levelled off, but they maintained a large portfolio of technological capabilities. They kept only essential activities in-house, whereas ISCs emerged as providers of comprehensive technology solutions and - as a response to an ever more integrated network of knowledge fields - embraced complexity (Beyazay-Odemis, 2016). Since the late 1980s, they have developed coordination capabilities and a technological profile that allows them to occupy a central position within global innovation networks and assume risk, responsibility, and reward for exploration and production of hydrocarbons alongside traditional IOCs (Acha and Cusmano, 2005, p. 19). In this sense, although having a different purpose and strategic mission in the value chain to IOCs, ISCs play the role of 'systems integrators' (Brusoni et al., 2001) because they are able – given their focus on technological capabilities to explore and develop complex oil reserves and construct oil production facilities- to combine and integrate advanced technologies (Acha, 2002).

Table 6, critically, also identifies that the main ISCs with globally dispersed operations have most of the inventive activities in advanced countries (mostly the US, UK and France). IOCs used to be larger investors in R&D but the ‘number of patents and other indicators’ show that ISCs are ‘more prominent incubators of new technology’, as companies such as ‘Schlumberger, Halliburton and Baker Hughes file more patents than most IOCs’ (Beyazay-Odemis, 2016, p. 49). As for technological learning in some emerging countries, when the technological frontier is pushed forward and KBC increases, local players in this industry suffer the consequences of ‘low absorptive capacity’ and a ‘lack of awareness regarding new technological scenarios’

(Mirimoghadam and Ghazinoory 2017, p. 262). In summary, this evidence (Figures 4, 6 and 7) suggests it was in around 1986 that the increasingly prominent role of these ISCs within the industry's knowledge system – reflected by the growth of their innovation stock and relative share of patents – began to trigger a growing divergence between our IC- and AMIC-based measures of spatial concentration.

Table 6: Main ISCs

7. Conclusions

This article has investigated the relationship between the dynamics of KBC and spatial patterns of international innovation in the upstream petroleum industry. Drawing on a set of quantitative measures to describe the dynamics of KBC and the industry's geography of innovation over a 40-year period, the paper developed three distinct indexes of variety, systemic complexity, and knowledge integration or decomposability as well as two measures of spatial concentration (IC; AMIC). Its focus is on long-term changes to the intensity of variety and complexity of the industry's knowledge base. Relying on unique empirical evidence from the petroleum industry, this research paves the way for future research on the role of KBC in shaping the international distribution of industrial activities and innovation.

One core contribution of our distinctions between variety, complexity and decomposability is that it nuances some of the competing claims within the literature regarding the spatial impact of complexity. Our results show that if KBC coincides with variety, and systemic interactions are restricted to a limited number of knowledge fields, the industry will remain relatively more open to new innovators and indicating that higher geographical dispersal of innovative activities is possible. This is because, up to the mid-1980s, there is an expansion of the knowledge base that became more diverse due to the efforts of specialized companies (Bridge, 2008). In contrast, the degree of complexity of the industry's knowledge base (including strong integration among different technological classes) started to rise in 1986. Coordination of different knowledge elements became more challenging, as cognitive and organisational proximities were increasingly needed. However, concentration in terms of inventor's country address (IC) did not increase.

However, our second key findings is that a pattern of differentiation between the spatial patterns of innovation generation and innovation ownership emerged in the mid-1980s and accelerated in the 1990s, when complexity increased, decomposability decreased, and the knowledge base became more difficult to manage for specialized companies. While at first glance this trend had no effect on the patterns of concentration of new inventors (IC), an alternative focus on 'assignees' (AMIC) leads to the reverse conclusion: spatial concentration in terms of ownership of new inventions increased.

Our third contribution is that we show that new governance arrangements emerged over time. There were three key patterns: (i) an increasing number of innovations were either assigned or co-assigned to MNCs; (ii) ISCs established themselves as both new system integrators and dominant innovators; and (iii) IOCs completed their move towards the outsourcing of integrated solutions (services and technologies) to handle exploration and extraction activities. Control and coordination of spatially dispersed innovation activities became the responsibility of multi-technology companies with most of the R&D activities in advanced economies, most of which were ISCs. They did not simply appropriate intellectual property developed in countries that own physical resources. Instead, they accumulated technological competences and actively offer "assets, equipment, technology, manpower and project management that enable oil companies, including IOCs, to explore and develop oil fields" (Beyazay-Odemis, 2016, p. 28).

This resonates with Cantwell's (1995; 2009) theory of globalization of technological development, regarding the establishment of international networks for technology creation and management. Cantwell (2009) argues that MNCs have greater potential to "benefit from a synergistic locational portfolio" (p. 35) of knowledge sources. Our findings further echo Mattes (2016) who showed that the dispersed organisational configurations of MNCs (with operations across several countries) can effectively assist them in absorbing knowledge from all over the world. In this respect, the case of upstream petroleum is unique in that the extension of the international networks for increasingly dispersed innovative activities was principally driven by the 'extensification' (Bridge, 2008) of extractive activities; a trend shaped by variable material conditions in different places. As such, this trend fits in with a wider recognition of functional fragmentation (Beyazay-Odemis, 2016) and the emergence of system integrators.

In sum, our results suggest that when KBC in upstream petroleum started to rise in 1986, the international distribution of innovative activities became more concentrated. However, this effect can only be observed by using information about a patent assignee's main country address. Moreover, higher concentration coincided with the emergence of new system integrators (Maleki et al. 2016), a role that became the prerogative of the largest oilfield ISCs.

Such conclusion shades new light on the claim that higher complexity leads to a rise in spatial concentration of innovation (Breschi 2000; Soreson 2005; Balland and Rigby 2017) and also fits in with Ernst (2005), ergo that limitations to the modular convergence of technology, organisational structures, and markets, can shape industrial dynamics and an industry's spatial patterns of innovation. A caveat, however, is that in upstream oil the trend of knowledge base decomposability during the 1970-2010 period mirrors that of complexity (measured using WADC). One cannot predict whether the same result would hold in other industries, in case these trends are found to diverge.

Like other studies that use longitudinal patent data, our study has further limitations. Patents cannot capture all forms of innovation (e.g. in this industry know-how that cannot be patented but it is frequently related to characteristics of local reservoirs) and systematic biases in data are also possible. For instance, the scope of a firm's patenting strategy may differ from country to country depending on the length, time, and level of protection offered by patent law, which shapes an innovator's incentive to rely on patents over other forms of safeguard. The propensity to patent can also vary across sectors (patent classes) and time because of the changing characteristics of the technological regime (for instance, the diffusion of software-based technologies). Furthermore, as noticed by authors such as Carricanzeaux et al (2001) and Cantwell and Mudambi (2011), the interaction between complexity and proximity in coordination can vary significantly depending on the industrial sector. Notwithstanding these potential problems, our results are based on the analysis of trends rather than the absolute levels of specific variables, which reduces the risk of systematic bias. In addition, different propensities to patent are considered while interpreting our results.

We further recognize that KBC is just one aspect of an industry's technological regime that shapes spatial patterns of innovation. Several related factors on a geopolitical, industrial, technological scale contribute to shape industrial dynamics in upstream oil (Baaij et al., 2011). In this article, we consider some key trends that are important to comprehend the relationship between the dynamics of KBC and spatial patterns of innovation. Moreover, following on from Hassani et al (2017), we acknowledge that upstream petroleum has progressively become more technology-intensive, with distinct technological classes following idiosyncratic life cycles. However, although we address the industry's technological context at different points in time, a life cycle analysis of individual technologies and their role in shaping industrial dynamics would demand a separate and more comprehensive enquiry – such as Huenteler et al's (2016) study of wind and solar technologies.

Methodologically, our approach to measuring complexity departs significantly from Hidalgo and Haussmann (2009), whose work has inspired recent studies such as Balland and Rigby (2017). We characterize the transformation of an industry's knowledge network in terms of the expansion of the range of the technologies it comprises vis-à-vis the emergence of systemic relationships between them and their strength. We further qualify our analysis by a graphical representation of the change in the network's structure (whose nodes are represented by technological classes) over the period under consideration, and by measuring and describing the nature of the organisational arrangements underlying innovative activities at different points in time.

We, therefore, see the potential for future research. One way of pursuing this would be to detail a more fine-grained statistical analysis of the correlation between dynamics of KBC and spatial patterns. In addition, although industrial analyses such as ours are context specific, we would welcome other studies that examined other industries - such as the aircraft industry – where there are inherently complex knowledge bases and a restricted number of companies whose headquarters and core R&D activities are located in key advanced countries.

Furthermore, we consider this work may have important implications for industrial and innovation policy in catching up countries. Our results suggest high innovation opportunities in this complex industry are open prevalently to countries with both existing technological capabilities and accumulated production experience. For latecomers to benefit, their industrial policies should help domestic players manage increasing complexity, mitigating its coordination costs and facilitating the integration of distributed catch-up processes. The study of the relationship between technological catch-up in energy sectors (including oil and gas) and knowledge base complexity will be the focus of a forthcoming article.

References:

Acha, V. L. (2002). Framing the past and future: the development and deployment of technological capabilities by the oil majors in the upstream petroleum industry (Doctoral dissertation, University of Sussex).

Acha, V. and Cusmano, L. (2005). Governance and co-ordination of distributed innovation processes: patterns of R&D co-operation in the upstream petroleum industry. Economics of Innovation and New Technology, **14**(1-2), 1-21.

Amin, A and Cohendet, P (2004), Architectures of knowledge: Firms, capabilities, and communities, Oxford University Press.

Amin, A and Cohendet, P (2005), Geographies of knowledge formation in firms", Industry and Innovation, **12**(4): 465-486.

Antonelli, C., Ed. (2011). Handbook on the Economic Complexity of Technological Change Cheltenham, Edward Elgar.

Athreye, S. and Cantwell J. (2007). Creating competition? Globalisation and the emergence of new technology producers. Research Policy **36**(2), 209-226.

Balland, P. A., Boschma, R. and Frenken, K. (2015). Proximity and innovation: From statics to dynamics. Regional Studies, **49**(6), 907-920.

Balland P.A. and Rigby D. (2017). The Geography of Complex Knowledge". Economic Geography, 93(1), 1-23.

Barreau, S. (2002). Innovations and External Growth Strategy: the Case of Oil and Gas Supply and Service Companies. Oil & Gas Science and Technology - Rev. IFP **57**(2):193-203.

Nam, Y. and Barnett, G. A. (2011), Globalization of technology: Network analysis of global patents and trademarks, Technological Forecasting and Social Change, **78**(8): 1471-1485.

Bayazay-Odemis, B. (2016). The Nature of the Firm in the Oil Industry: International Oil Companies in Global Business, NT-Oxford, Routledge.

Berggren, C., Bergek, A., Bengtsson, L., Hobday, M., & Söderlund, J. (2013). Knowledge integration and innovation: Critical challenges facing international technology-based firms. Oxford University Press.

Boschma, R. and Iammarino, S. (2009). Related Variety, Trade Linkages, and Regional Growth in Italy. Economic Geography **85**(3): 289-311.

Breschi, S. and Malerba, F. (1997). Sectoral innovation systems: technological regimes, Schumpeterian dynamics, and spatial boundaries, in Systems of innovation: Technologies, institutions and organizations, 130-156.

Breschi, S. (2000). The Geography of Innovation: A Cross-sector Analysis." Regional Studies **34**(3): 213-229.

Bridge, G. and Wood, A. (2005). Geographies of knowledge, practices of globalization: learning from the oil exploration and production industry. Area, **37**(2):199-208.

Bridge, G. (2008). Global production networks and the extractive sector: governing resource-based development. Journal of Economic Geography, **8**(3): 389-419.

Brusoni, S., Prencipe, A. and Pavitt, K. (2001). Knowledge specialization, organizational coupling, and the boundaries of the firm: why do firms know more than they make? Administrative science quarterly, **46**(4):597-621.

Cantwell, J. (1995). The globalisation of technology: what remains of the product cycle model?" Cambridge Journal of Economics **19**(1):155-174.

Cantwell, J (2009). Location of the Multinational Enterprise, Journal of Business Studies, 40(1): 35-41.

Cantwell, J. A, Mudambi, R (2011), Physical attraction and the geography of knowledge sourcing in multinational enterprises, Global Strategy Journal, **1**(3-4): 206-232.

Carrincazeaux, C. (2001). Geographic Proximity and localisation of corporate R&D activities. Research Policy, **30**(5), 777-789.

Carrincazeaux, C. and Coris, M. (2011). Proximity and innovation, in Cooke P., Asheim B., Boschma R., Martin R., Schwartz D. and Todling F. The Handbook on Regional Innovation and Growth, EE - Cheltenham, 269-281.

Chafcouloff, S., Michel, G. Trice G, Clark M., Cosad C and Forbes K. (1995). Integrated services. Oilfield Review, summer 1995, 11-25

Chesbrough, H. W. and Teece, D. J. (1996). Organizing for Innovation. (cover story)." Harvard Business Review **74**(1):65-73.

Dale, C., Osegowitsch, T. and Collinson, S. (2014). Disintegration and de-internationalization: changing vertical and international scope and the case of the oil and gas industry. Advances in International Management, **27(**1):487-516.

Danguy J. (2017) Globalization of innovation production: A patent-based industry analysis, Science and Public Policy, **44**(1): 75-94

Dantas E and Bell M (2011), The Co-Evolution of Firm-Centered Knowledge Networks and Capabilities in Late Industrializing Countries: The Case of Petrobras in the Offshore Oil Innovation System in Brazil, World Development, **39** (9)1570–1591.

Ernst, D. (2005). Complexity and Internationalization of Innovation: Why is Chip Design Moving to Asia? International Journal of Innovation Management **9**(1), 47-73.

Frenken, K., Van Oort, F. and Verburg, T. (2007). Related variety, unrelated variety and regional economic growth. Regional studies, **41**(5):685-697.

Hall, B. H. (2000). A note on the bias in the Herfindahl based on count data. *Unpublished note, http://emlab. berkeley. edu/users/bhhall/hhibias.pdf*.

Hassani, H, Silva, E S, and Al Kaabi, A M (2017), The role of innovation and technology in sustaining the petroleum and petrochemical industry, Technological Forecasting and Social Change, **119**, 1-17.

He J and Fallah M.H. (2009). Is inventor network structure a predictor of cluster evolution? Technological Forecasting & Social Change, **76**(1): 91–106.

Herstad, S. J, Aslesen, H. W, Ebersberger B (2014), On industrial knowledge bases, commercial opportunities and global innovation network linkages, Research Policy, **43**(3): 495-504

Hidalgo, C., and Hausmann, R. 2009. "The building blocks of economic complexity". Proceedings of the National Academy of Sciences, **106**, 10570–5.

Hu, Y., Scherngell, T., Man, S.N., Wang, Y (2013). Is the United States still dominant in the global pharmaceutical innovation network? PlosOne, **8**(11): e77247.

Ivanova, I, Strand, Ø., Kushnir, D. and Leydesdorff, L (2017). Economic and technological complexity: A model study of indexes of knowledge-based innovation systems. Technological Forecasting and Social Change. (in press) https://doi.org/10.1016/j.techfore.2017.04.007.

Krafft, J., Quatraro, F. and Saviotti, P (2011). "The knowledge-base evolution in biotechnology: a social network analysis." Economics of Innovation and New Technology **20**(5): 445-475.

Krafft, J. Quatraro, F and Saviotti, P. P (2014), Knowledge characteristics and the dynamics of technological alliances in pharmaceuticals: empirical evidence from Europe, US and Japan, Journal of Evolutionary Economics, **24**(3), 587-622.

Leamer E.E., Storper M. (2014) The Economic Geography of the Internet Age. In: Cantwell J. (eds) Location of International Business Activities. Palgrave Macmillan, London.

Liu, F Sun, Y (2009). A comparison of the spatial distribution of innovative activities in China and the US. Technological Forecasting and Social Change. **76**(6): 797:805.

Maleki, A., Rosiello, A. and Wield, D. (2016). The effects of the dynamics of knowledge base complexity on Schumpeterian patterns of innovation: the upstream petroleum industry, R&D Management, (in press) http://dx.doi:10.1111/radm.12251

Marsili, O. (2001). The anatomy and evolution of industries: technological change and industrial dynamics, Edward Elgar, Cheltenham.

Mattes, J. (2016). The geography of innovation in multinational companies: internal distribution and external embeddedness, in (Eds) Shearmur, R., Carrincazeaux, C. and Doloreux, D. Handbook on the Geographies of Innovation, 399-418.

Mirimoghadam, M. and Ghazinoory, S (2015). An institutional analysis of technological learning in Iran's oil and gas industry: Case study of south pars gas field development. Technological Forecasting and Social Change, **122**(3): 262-274

Mommer, B. (2002). Global oil and the nation state. Oxford University Press, USA.

Motoyama, Y., Cao, C. and Appelbaum, R (2014). Observing regional divergence of Chinese nanotechnology centers. Technological Forecasting and Social Change, **81**(1): 11-21.

Neal, H., Bell, M. R. G., Hansen, C. A. and Siegfried, R. W. (2007). Oil and gas technology development. National Petroleum Council Topic Paper, 26.

OECD (2009). OECD patent statistics manual. Paris, OECD

Oltra, V. and Saint Jean M (2009) Sectoral systems of environmental innovation: an application to the French automotive industry. Technological Forecasting and Social Change. **76** (4): 567-583.

Patel, P. and Pavitt, K. (1997). The technological competencies of the world's largest firms: complex and path-dependent, but not much variety. Research policy, **26**(2):141-156.

Patel, P. and Pavitt, K. (1991). Large firms in the production of the world's technology: an important case of" non-globalisation". Journal of International Business Studies, 1-21.

Pavitt, K., Ed. (1999). Technology, Management and Systems of Innovation. Cheltenham, Edward Elgar.

Rycroft R. W. (2007). Does cooperation absorb complexity? Innovation networks and the speed and spread of complex technological innovation. Technological Forecasting and Social Change, **74**(5), 565-578.

Saviotti, P. P. (2011). Knowledge, Complexity and Networks. Handbook On The Economic Complexity Of Technological Change. C. Antonelli. Cheltenham, Edward Elgar.

Scaringella, L and Radziwon, A (2017). Innovation, entrepreneurial, knowledge, and business ecosystems: Old wine in new bottles? Technological Forecasting and Social Change (in press) https://doi.org/10.1016/j.techfore.2017.09.023.

Singh, K. (1997). The impact of technological complexity and interfirm cooperation on business survival. Academy of Management Journal, **40**(2): 339-367.

Siedschlag, I., Smith, D., Turcu, C. and Zhang, X. (2013). What determines the location choice of R&D activities by multinational firms? Research Policy, **42**(8):1420-1430.

Sorenson, O. (2005). Social Networks, Informational Complexity and Industrial Geography, in (Eds) Fornahl, D., Zellner, C., Audretsch, D. and Sorenson, O. The Role of Labour Mobility and Informal Networks for Knowledge Transfer. Springer US, 79-96.

Sorenson, O., Rivkin, J. W., and Fleming L. (2006). "Complexity, networks and knowledge flow." Research Policy **35**(7):994-1017.

Vertova, G. (2002). A historical investigation of the geography of innovative activities. Structural Change and Economic Dynamics **13**(3): 259-283.

Yayavaram, S. and Ahuja, G. (2008). Decomposability in knowledge structures and its impact on the usefulness of inventions and knowledge base malleability. Administrative Science Quarterly, **53**(2):333-362.

Yayavaram, S. and Chen, W. R. (2015). Changes in firm knowledge couplings and firm innovation performance: The moderating role of technological complexity. Strategic Management Journal, **36**(3), 377-396.

Wang, Q. and von Tunzelmann, N. (2000). "Complexity and the functions of the firm: breadth and depth." Research Policy **29**(7-8):805-818.

APPENDIX 1: Entropy Index

The entropy index is used in information theory in thermodynamics to measure the degree of disorder and/or randomness. Recently, it has been employed to study the dynamics of sectoral knowledge bases (Krafft et al., 2011). Its main advantage is decomposability to 'within' and 'between' parts, enabling us to study both *related variety (RV)* and *unrelated variety (UV),* at the same time. Unrelated variety refers to the degree of disorder or variety 'across' the main categories, while related variety captures the sum of the weighted entropy or the average degree of disorder 'within' categories (Frenken et al., 2007).

We use entropy to explore the sources of dynamics in variety measured by the *total variety (TV)* index. For formal notification, let C_g refer to technological classes at the 4-digit level where $g = (1 \ldots G)$. All sub-classes i at disaggregated level (7-digit here) fall under one 4-digit class, because of the nature of the hierarchical classification system. Therefore, the share of patents in 4-digit classes P_g is given by the sum of p_i shares of patents in the 7-digit sub-classes:

$$P_g = \sum_{i \in C_g} p_i$$

Unrelated variety is drawn from the entropy index formula based on the shares at the 4-digit level (P_g):

$$UV = \sum_{g=1}^{G} P_g \ln\left(\frac{1}{P_g}\right)$$

Related variety is the weighted sum of entropy for shares of 7-digit sub classes (p_i) 'within' each 4-digit class, given by:

$$RV = \sum_{g=1}^{G} P_g V_g$$

Where:

$$V_g = \sum_{i \in C_g}^{G} \frac{p_i}{P_g} \ln\left(\frac{1}{p_i / P_g}\right)$$

APPENDIX 2: Measures of Knowledge Base Complexity

We employed SNA to characterize the connectivity of the network as a measure for complexity. A matrix of co-occurrence of technological classes is formed to represent the knowledge network where the value of each cell is the number of inventions for which two technological classes appeared jointly together (Krafft et al., 2011).

The *degree* of *centrality* of a node is used as one of the centrality measures, describing the strength of the level of connectivity of a node. Formally, the following equation expresses the measure of *degree* of *centrality (DC):*

$$DC_n = \sum_{i \in N \neq n} l_{ni} \qquad (1)$$

Where ***n*** represents the nodes and ***l*** represent the links.

The *degree* of *centrality* is defined as the number of links of one node with other nodes of the network. Because this measure is affected by the network size, it is often divided by its maximum value to provide a normalized proxy, as shown in the following equation:

$$NDC = DC_n / (N-1) \qquad (2)$$

In order to create a measure of connectivity at the level of a network, we rely on the *average* of the degree of centrality of all nodes in the network. Following (Krafft et al., 2011), we used the *average* measure of *degree* of *centrality*, weighted by relative frequency (the number of patents in the class n [Pn] divided by the total number of patents). This considers the highly unequal strength of the nodes, giving higher weights to important technological classes. Accordingly, the measure of complexity of the knowledge is the WADC as follows:

$$WADC = \sum_n [NDC_n * (P_n / \sum_n P_n)] \qquad (3)$$

APPENDIX 3: New technological classes in the knowledge network

Figure 9 shows the strength of some selected nodes (technological classes) within the knowledge network. Classes such as C09K0008 (compositions for well drilling) E21B0034 (valve arrangements for boreholes or wells) and E21B0010 (drill bits) began to surge rapidly starting in the mid-70s, which reflects a quest to explore new oil sources and produce in ever harsher environments.

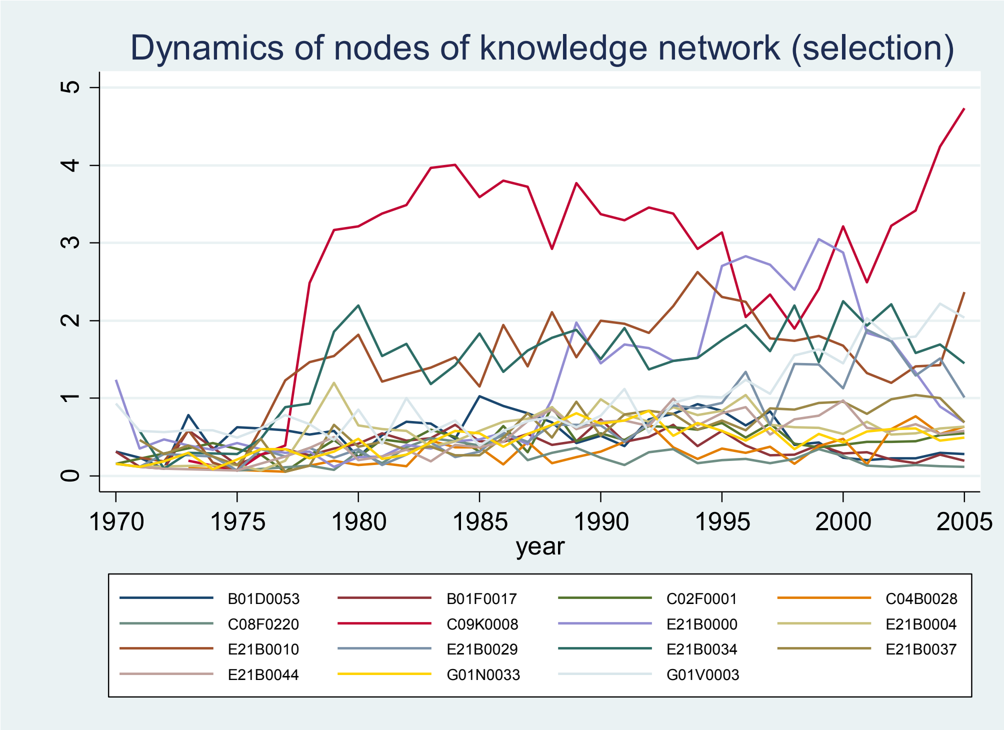


Figure 9: Strength of Knowledge Network Nodes (technological classes)

Figure 10 portrays emerging co-occurrences among core technological classes. For instance, around the 1970s classes such as E210043 (Methods or apparatus for obtaining oil, gas) and E210033 (technologies for Sealing or packing wells) began to combine with E210034 (valve arrangements), as technical solutions for the well's development process were required.

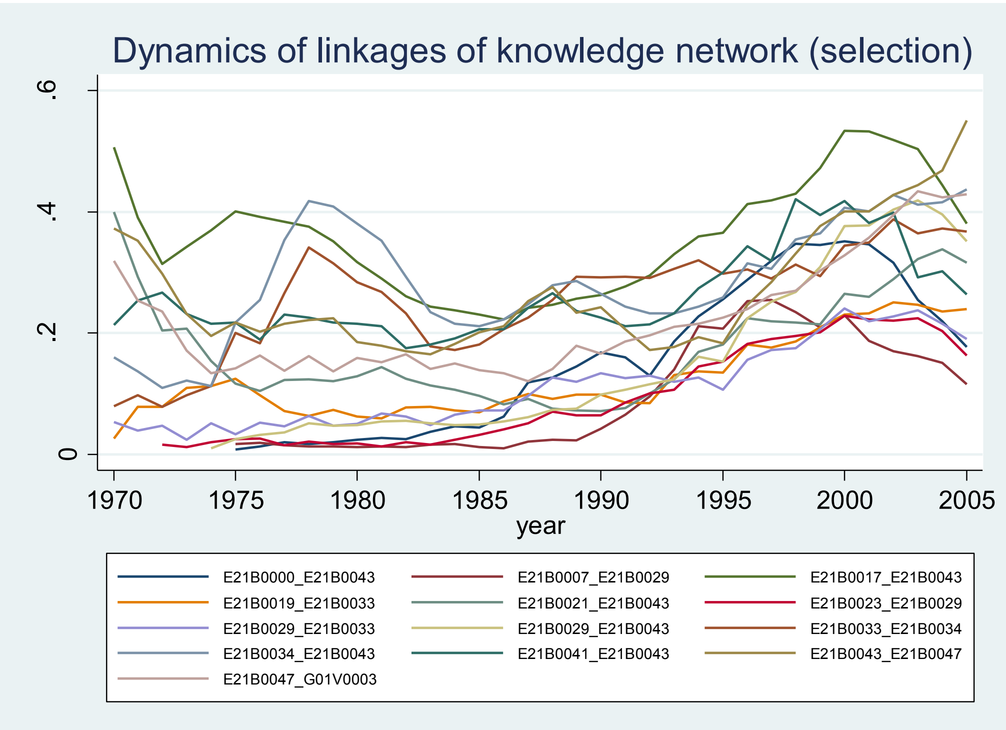


Figure 10: Strength of Linkages among Nodes (technological classes)

Table 1:

Aggregation Level of IPC class	The number of IPC classes	Descriptive statistics of patents in IPC classes			
		Mean	Std. Dev.	Min	Max
3 dig IPC	118	561.94	2333.03	1	24003
4 dig IPC	600	125.93	1019.50	1	23921
7 dig IPC	4301	27.69	217.59	1	9304
9 dig IPC	16422	10.56	65.11	1	2152

Table 2:

Rank	One digit IPC class	Freq.	Percent	Cum.
1	E:FIXED CONSTRUCTIONS	26,000	39.21	39.2
2	C:CHEMISTRY; METALLURGY	13,101	19.76	59
3	B:PERFORMING OPERATIONS; TRANSPORTING	8,988	13.55	72.5
4	G:GPHYSICS	8,245	12.43	85
5	F:MECHANICAL ENGINEERING; LIGHTING; HEATING; WEAPONS; BLASTING	6,978	10.52	95.5
6	H:ELECTRICITY	1,707	2.57	98.1
7	A:HUMAN NECESSITIES	1,037	1.56	99.6
8	D:TEXTILES; PAPER	253	0.38	100
Total		66309	100	100

Table 3:

top 20 3-digit IPC class

Rank	3-digit IPC class	Count	Percent	Cum.	Description
1	E21	24003	36.2	36.2	EARTH OR ROCK DRILLING; MINING
2	G01	6246	9.42	45.62	MEASURING; TESTING
3	C09	3829	5.77	51.39	DYES; PAINTS; POLISHES; NATURAL RESINS; ADHESIVES;
4	F16	3701	5.58	56.97	ENGINEERING ELEMENTS OR UNITS; GENERAL MEASURES FOR PRODUCING AND MAINTAINING EFFECTIVE FUNCTIONING OF MACHINES OR INSTALLATIONS; THERMAL INSULATION IN GENERAL
5	B01	3042	4.59	61.56	PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL
6	C10	1981	2.99	64.55	PETROLEUM, GAS OR COKE INDUSTRIES; TECHNICAL GASES CONTAINING CARBON MONOXIDE; FUELS; LUBRICANTS; PEAT
7	C08	1889	2.85	67.4	ORGANIC MACROMOLECULAR COMPOUNDS; THEIR PREPARATION OR CHEMICAL WORKING-UP; COMPOSITIONS BASED THEREON
8	E02	1639	2.47	69.87	HYDRAULIC ENGINEERING; FOUNDATIONS; SOIL-SHIFTING
9	B63	1435	2.16	72.03	SHIPS OR OTHER WATERBORNE VESSELS; RELATED EQUIPMENT
10	C07	1169	1.76	73.8	ORGANIC CHEMISTRY
11	F04	986	1.49	75.28	POSITIVE-DISPLACEMENT MACHINES FOR LIQUIDS; PUMPS FOR LIQUIDS OR ELASTIC FLUIDS
12	G06	967	1.46	76.74	COMPUTING; CALCULATING; COUNTING
13	C04	853	1.29	78.03	CEMENTS; CONCRETE; ARTIFICIAL STONE; CERAMICS; REFRACTORIES
14	C02	819	1.24	79.26	TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE
15	B23	688	1.04	80.3	MACHINE TOOLS; METAL-WORKING NOT OTHERWISE PROVIDED FOR
16	H01	646	0.97	81.28	BASIC ELECTRIC ELEMENTS
17	C01	598	0.9	82.18	INORGANIC CHEMISTRY
18	C23	553	0.83	83.01	COATING METALLIC MATERIAL
19	H04	534	0.81	83.82	ELECTRIC COMMUNICATION TECHNIQUE
20	B21	401	0.6	84.42	MECHANICAL METAL-WORKING WITHOUT ESSENTIALLY REMOVING MATERIAL; PUNCHING METAL

Table 4:

top 20 4-digit IPC class

Rank	4 dig IPC class	Count	Percent	Cum. Percent	Description
1	E21B	23921	31.66	31.66	EARTH OR ROCK DRILLING; OBTAINING OIL, GAS, WATER, SOLUBLE OR MELTABLE MATERIALS OR A SLURRY OF MINERALS FROM WELLS
2	G01V	4410	5.84	37.5	GEOPHYSICS; GRAVITATIONAL MEASUREMENTS; DETECTING MASSES OR OBJECTS
3	C09K	3598	4.76	42.26	MATERIALS FOR APPLICATIONS NOT OTHERWISE PROVIDED FOR; APPLICATIONS OF MATERIALS NOT OTHERWISE PROVIDED FOR
4	F16L	2120	2.81	45.07	PIPES; JOINTS OR FITTINGS FOR PIPES; SUPPORTS FOR PIPES, CABLES OR PROTECTIVE TUBING; MEANS FOR THERMAL INSULATION IN GENERAL
5	B01D	2045	2.71	47.77	PHYSICAL OR CHEMICAL PROCESSES OR APPARATUS IN GENERAL: SEPARATION
6	G01N	1629	2.16	49.93	INVESTIGATING OR ANALYSING MATERIALS BY DETERMINING THEIR CHEMICAL OR PHYSICAL PROPERTIES
7	B63B	1301	1.72	51.65	SHIPS OR OTHER WATERBORNE VESSELS; EQUIPMENT FOR SHIPPING
8	C10G	1232	1.63	53.28	CRACKING HYDROCARBON OILS; PRODUCTION OF LIQUID HYDROCARBON MIXTURES, e.g. BY DESTRUCTIVE HYDROGENATION, OLIGOMERISATION, POLYMERISATION ; RECOVERY OF HYDROCARBON OILS FROM OIL-SHALE, OIL-SAND, OR GASES; REFINING MIXTURES MAINLY CONSISTING OF HYDROCARBONS; REFORMING OF NAPHTHA; MINERAL WAXES
9	E02B	1094	1.45	54.73	HYDRAULIC ENGINEERING
10	E02D	881	1.17	55.89	FOUNDATIONS; EXCAVATIONS; EMBANKMENTS ; UNDERGROUND OR UNDERWATER STRUCTURES
11	C08L	876	1.16	57.05	COMPOSITIONS OF MACROMOLECULAR COMPOUNDS
12	C04B	852	1.13	58.18	LIME; MAGNESIA; SLAG; CEMENTS; COMPOSITIONS THEREOF, e.g. MORTARS, CONCRETE OR LIKE BUILDING MATERIALS; ARTIFICIAL STONE; CERAMICS ; REFRACTORIES; TREATMENT OF NATURAL STONE
13	G06F	816	1.08	59.26	ELECTRIC DIGITAL DATA PROCESSING
14	C07C	806	1.07	60.33	ACYCLIC OR CARBOCYCLIC COMPOUNDS
15	C02F	763	1.01	61.34	TREATMENT OF WATER, WASTE WATER, SEWAGE, OR SLUDGE
16	F16K	736	0.97	62.31	VALVES; TAPS; COCKS; ACTUATING-FLOATS; DEVICES FOR VENTING OR AERATING
17	B01F	720	0.95	63.27	MIXING, e.g. DISSOLVING, EMULSIFYING, DISPERSING
18	C08F	717	0.95	64.21	MACROMOLECULAR COMPOUNDS OBTAINED BY REACTIONS ONLY INVOLVING CARBON-TO-CARBON UNSATURATED BONDS
19	F04B	681	0.9	65.12	POSITIVE-DISPLACEMENT MACHINES FOR LIQUIDS; PUMPS
20	B01J	654	0.87	65.98	CHEMICAL OR PHYSICAL PROCESSES, e.g. CATALYSIS, COLLOID CHEMISTRY; THEIR RELEVANT APPARATUS

Table 5:

top 20 7- digit IPC class

Rank	7 dig IPC class	Count	Percent	Cum. Percent	Class description
1	E21B-043	9304	7.81	7.81	Methods or apparatus for obtaining oil, gas, water, soluble or meltable materials or a slurry of minerals from wells
2	E21B-033	5310	4.46	12.27	Sealing or packing boreholes or wells
3	E21B-047	3994	3.35	15.62	Survey of boreholes or wells
4	E21B-017	3270	2.75	18.37	Drilling rods or pipes; Flexible drill strings; Kellies; Drill collars; Sucker rods; Casings; Tubings
5	E21B-007	2635	2.21	20.58	Special methods or apparatus for deep-drilling
6	E21B-023	2531	2.13	22.71	Apparatus for displacing, setting, locking, releasing or removing tools, packers or the like in boreholes or wells
7	G01V-001	2488	2.09	24.8	Seismology; Seismic or acoustic prospecting or detecting
8	E21B-000	2161	1.81	26.61	
9	C09K-007	1980	1.66	28.27	Aqueous fluids containing organic or inorganic compounds
10	E21B-021	1917	1.61	29.88	Methods or apparatus for flushing boreholes, e.g. by use of exhaust air from motor
11	E21B-019	1892	1.59	31.47	Handling rods, casings, tubes or the like outside the borehole, e.g. in the derrick; Apparatus for feeding the rods or cables
12	E21B-034	1881	1.58	33.05	Valve arrangements for boreholes or wells
13	E21B-010	1800	1.51	34.56	Drill bits
14	E21B-049	1800	1.51	36.07	Testing the nature of borehole walls; Formation testing; Methods or apparatus for obtaining samples of soil or well fluids, specially adapted to earth drilling or wells
15	G01V-003	1539	1.29	37.37	Electric or magnetic prospecting or detecting; Measuring magnetic field characteristics of the earth, e.g. declination or deviation
16	C09K-008	1515	1.27	38.64	Compositions for drilling of boreholes or wells; Compositions for treating boreholes or wells, e.g. for completion or for remedial operations
17	E21B-041	1174	0.99	39.62	Equipment or details not covered by groups
18	E21B-029	1126	0.95	40.57	Cutting or destroying pipes, packers, plugs, or wire lines, located in boreholes or wells, e.g. cutting of damaged pipes, of windows; Deforming of pipes in boreholes or wells; Reconditioning of well casings while in the ground
19	E02B-017	921	0.77	41.34	Artificial islands mounted on piles or like supports, e.g. platforms on reusable legs; Construction methods therefor
20	E21B-037	882	0.74	42.08	Methods or apparatus for cleaning boreholes or wells

Table 6:

Country of invention of patents owned by the 5 largest oilfield Integrated Service Companies: Schlumberger, Halliburton, Baker Hughes, Weatherford, and Smith International			
Developed countries		**Developing countries**	
United States of America	7689	Russian Federation	86
United Kingdom	1118	United Arab Emirates	58
France	735	China	57
Germany	266	Malaysia	28
Canada	252	Saudi Arabia	27
Norway	235	Indonesia	24
Netherlands	143	Oman	19
Japan	122	Brazil	18
Belgium	44	Venezuela	16
Australia	40	India	13
Italy	24	Qatar	8
Singapore	19	Mexico	7
Denmark	15	Argentina	6
New Zealand	11	Colombia	6
Other	32	Other	60
Total	10745	Total	433
Percent	96.13	Percent	3.87

i Whenever necessary, fractional counting was employed to assign the correct share of an invention to specific inventors and assignees. In addition, to avoid the problems with identifying assignees in patent families, we crosscheck that information with the one concerning the country of primary application.

ii At least 10% of inventions developed by each organization in any specific country. This intervention is specifically designed to re-assign patents allotted to places such as Virgin Islands, Dutch Antilles, and Panama, where no significant R&D activities are conducted.